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Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future

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A B S T R A C T

Biofuels are identified as the potential solution for depleting fossil fuel reserves, increasing oil prices, and providing a clean, renewable energy source. The major barrier preventing the commercialization of lignocellulosic biorefineries is the complex conversion process and their respective supply chain. Efficient supply chain management of a lignocellulosic biomass is crucial for success of second generation biofuels. This paper systematically describes energy needs, energy targets, biofuel feedstocks, conversion processes, and finally provides a comprehensive review of Biomass Supply Chain (BSC) design and modeling. Specifically, the paper presents a detailed review of mathematical programming models developed for BSC and identifies key challenges and potential future work. This review will provide readers with a starting point for understanding biomass feedstocks and biofuel production as well as detailed analysis of the BSC modeling and design.

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1. Introduction

Countries all over the world are focusing on renewable energy resources as an attractive option for achieving future energy security. Feedstocks that can be used for food or feed have been extensively utilized for biofuel production [1]. Recently, this trend has shifted and the focus is now on utilizing lignocellulosic biomass and non-food products for biofuel production purposes, and thus enhancing food and energy security. The shift to non-food sources as raw material is not easy and is full of challenges starting from cultivation of biomass to its conversion technology for biofuel production [2]. The increasing trend of energy consumption has compelled countries all over the world to set targets and mandates for the future biofuel production. Corn and sugarcane based ethanol production are well-established technologies. Presently, most of the research efforts are directed towards developing an efficient conversion technology and BSC system for lignocellulosic biomass feedstocks. This literature review addresses the reasons for an increased focus on biomass as an energy source, summarizes the present energy situation, emphasizes issues surrounding BSC, provides detailed review of mathematical modeling of BSC, and highlights the importance of supply chain management. This paper is organized into three major sections. Section 1 introduces the most recent world energy trends, biofuel targets, biomass feedstocks, biomass conversion technologies and BSC. Section 2 describes review methodology. Section 3 describes analysis and main features of reviewed articles categorized according to the taxonomy discussed in Section 2. Section 4 provides an overview of issues and challenges and describes potential future work. Section 5 presents the conclusions of the work.

1.1. Energy trends

The world's energy consumption experienced the largest increase since 1973, of 5.6% in 2010. The energy consumption in China grew by 11.2% in 2010 thus surpassing the U.S. and becoming the world's largest energy consumer by using 20.3% of global energy. The world's leading fuel was oil, contributing 33.6% of global energy consumption in 2010. The global oil consumption grew by 3.1% or 2.7 million barrels; whereas, the oil production did not match the consumption and increased only 2.2% or 1.8 million barrels/day [3]. The world energy crises have focused the attention of researchers to exploring alternative renewable energy sources. Presently, the conversion of biomass for heat and power generation is the most common form of bioenergy. Biofuels production from starch, sugar, and oil seeds is technically feasible and is a well-developed, commercialized technology. The world's biofuel production grew by 13.8% in 2010, mostly driven by the U.S. and Brazil [3]. Fig. 1 shows the increase in world's biofuel production from the year 2000–2011. North America and South and Central America are leading producers of biofuels, mainly ethanol, whereas, Europe and Eurasia are the dominant producers of biodiesel [3]. U.S. ethanol production has increased as the result of ambitious biofuel targets and also due to widespread availability of flex-fuel vehicles (Fig. 2) [4]. Most of the ethanol consumed by the U.S. is produced domestically which also makes the U.S., the world's largest producer of ethanol by volume. The increase in the biodiesel production and consumption in 2011 was attributed to the Renewable Fuel Standards [5] target levels set for the production of biofuels (Fig. 3) [6]. The increase in the prices of food commodities in 2008 was attributed with growing global demand for food commodities, crop failures in various parts of the world, a major drop in the value of the U.S. dollar, and the growth of the biofuel industry [7]. Some studies claim that the increase in prices of food commodities was due to biofuel production, but others disagree, associating the hike in oil prices as the only reason [8]. A decade ago, China started

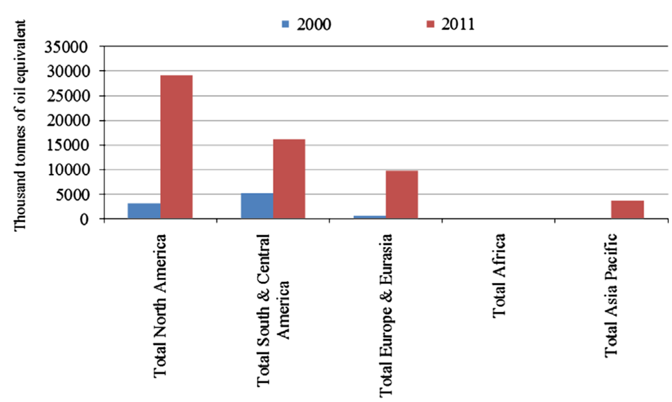


Fig. 1. World's biofuel production in thousands of tonnes oil equivalent [3].

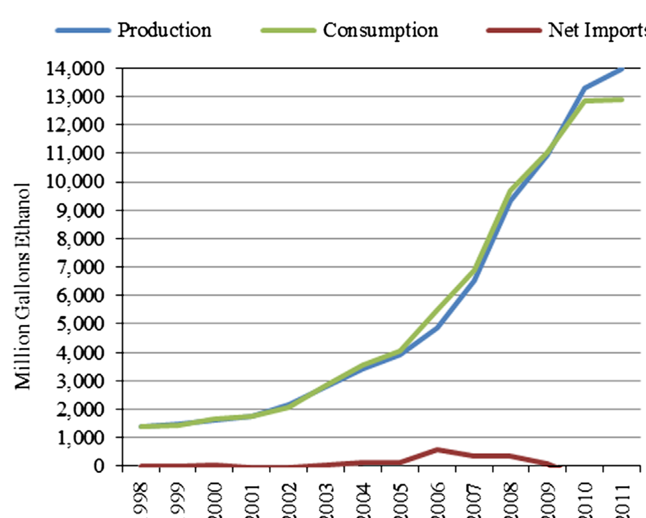


Fig. 2. U.S. production, consumption, and Trade* of fuel ethanol (*Trade includes small changes in stock) [4].

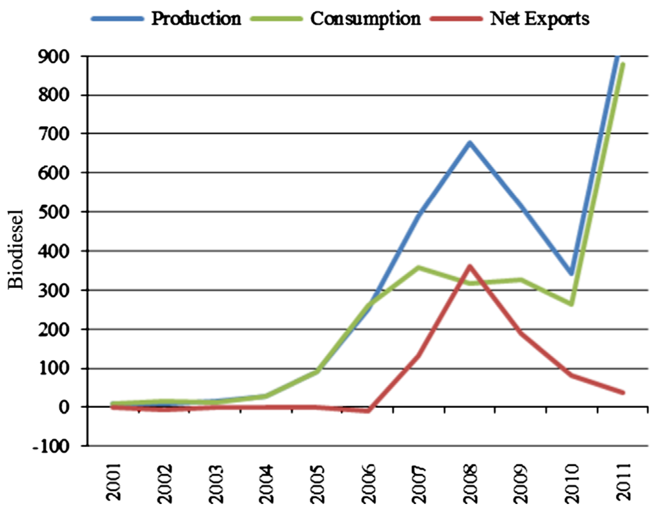


Fig. 3. U.S. Biodiesel production, consumption, and net exports [6].

bioethanol production from corn. As a result, there was an extreme shortage and drastic increase in food prices. In 2007, the Chinese government banned use of grains for biofuels [9]. It is clear that biofuel production affects the prices of food commodities by competing with agriculture and using arable land otherwise used for food production.

The U.S. is the leading producer and exporter of corn [7]; whereas, Brazil is the leading grower and producer of sugarcane in the world [10]. Both countries utilize these crops for ethanol production. Additionally, China and Europe use cassava and rapeseed for biofuel production, respectively [9]. The increasing demand for ethanol has led to an intense competition for the availability of corn, starch-based grains, and sugarcane for food, fuel, and export markets [11]. Moreover, if we continue to use major crops such as corn and sugarcane for biofuel production, it will require large quantities of crop harvested in a short-period of time. Thus, increasing the storage cost and area required for year-around supply of feedstock to the biorefinery [12] and also increasing the risk of land use change and its associated emissions. Therefore, it is important to investigate and explore alternative resources for biofuel production.

1.2. Renewable energy targets

In order to deal with the increasing prices and demand of crude oil, mitigating, greenhouse gas emissions, energy and food security, support for rural economic development, reducing dependence on foreign oil, and achieving environmental sustainability, the world is relying on renewable fuels for the future [13]. Countries all over the world have recognized the importance of renewable resources and have developed mandates, incentives, and policies to accelerate the implementation of biofuel/bioenergy systems [14,15]. The Energy Independence and Security Act (EISA) of 2007 amended and increased the Renewable Fuels Standards [5] in the U.S. EISA of 2007 mandates that 36 billion gallons of renewable fuel be produced by 2022 of which about 15 billion gallons will be conventional biofuels (renewable fuel derived from corn starch) and the remaining 21 billion gallons will be from advanced biofuels (renewable fuel derived from renewable biomass, not considering ethanol from corn starch). The European Union has ambitious growth targets for achieving 24% of transport fuel, 14% of bioelectricity, and 63% heat from biomass by 2020 [16]. Brazil, China, and India intend to replace 5 to 20% of on-road gasoline consumption with ethanol in the future [14]. In order to achieve the set targets, countries are focusing on advanced biofuels from lignocellulosic biomass such as agricultural residue, herbaceous crops, short rotation woody crops, urban woody waste and secondary mill residue, and forest biomass. These lignocellulosic biomass feedstocks are recognized as the future renewable energy sources [5]. The transition to lignocellulosic feedstocks for biofuel production will require advancement in the area of agricultural engineering, biochemistry, biotechnology, modeling, and optimization.

1.3. Biomass feedstocks and conversion technology

Fig. 4 presents the different types of biomass feedstocks used for biofuel production. The terms first, second, and third generation are used interchangeably for feedstocks and processes. For example, corn and sugarcane represent first-generation ethanol feedstocks, and bio-chemical conversion represents first-generation ethanol production process. Non-food crops such as herbaceous energy crops and forest biomass represent second-generation ethanol feedstocks, and thermo-chemical conversion represent second-generation ethanol production process [17]. Various types of biomass can be converted into heat, power, biofuels or a combination by using specific technologies [18]. The heat and electric generation is one of the most common and widely used forms of bioenergy. The technology to convert first-generation feedstocks into biofuels is also well-developed and commercialized. The major barrier is in the commercialization of biofuels from second-generation and third-generation feedstocks. The economic and technical aspects related to complex conversion process and supply chain management of second-generation feedstocks limits its application to large-scale biorefineries. Bioenergy from third-generation feedstock such as microalgae has great potential, but again there are several scientific and technical barriers associated with photobiorector design, microalgal biomass harvesting, drying, and processing [19].

Generally biorefineries are classified into four types: starch-based, sugar-based, oil-based, and lignocellulosic biomass-based. The technology used for conversion depends on the type of raw material and the desired final product (Fig. 5). The energy from biomass can be utilized by direct combustion or by converting biomass to more valued fuels such as charcoal (solid residue produced by slow pyrolysis of carbonaceous raw material), biogas (gas produced by anaerobic digestion or fermentation of organic matter), liquid fuels (biodiesel, bioethanol) and producer gas (mixture of gases produced by gasification of organic matter at relatively low temperatures) [20]. The conversion technologies are direct combustion, thermo-chemical processes (pyrolysis, gasification), bio-chemical processes (anaerobic digestion, fermentation) and physico-chemical processes (biodiesel) [21]. The lignocellulosic biorefineries are also categorized into two types: basic lignocellulosic biorefinery (BLCBR) and integrated/advanced lignocellulosic biorefinery (ILCBR) [22]. The BLCBR produces bioethanol by a biochemical conversion process along with production of steam and electricity or combined heat and power; whereas ILCBR consists of integrated gasification combined cycle to produce biosyngas and combined with heat and power production and also biochemical conversion to produce ethanol. The other route could be pyrolysis of biomass to produce bio-oil instead of gasification to produce syngas [22]. Table 1 provides a summary of bioethanol plants using lignocellulosic feedstocks. Pilot plants have successfully demonstrated the production of ethanol from feedstocks such as agricultural waste. Though, some feedstocks such as wood waste, particularly softwoods, are still under investigation. The demonstration plants will provide headway for large-scale production of second generation biofuels [23]. The conversion technology for lignocellulosic biomass is associated with some major issues which need to be addressed before its commercialization. The issues associated with biochemical conversion processes are: development of cost-effective pre-treatment process which minimizes lignin

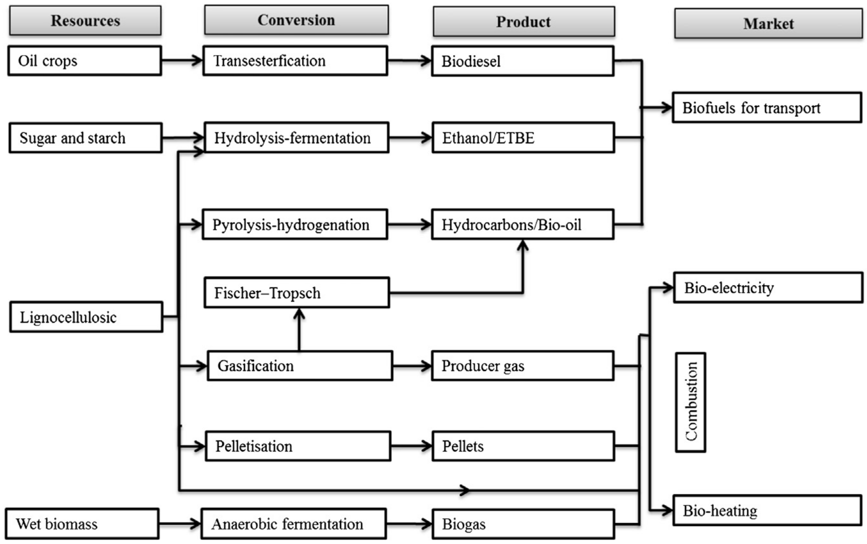


Fig. 4. Classification of biofuels and feedstocks [17,19,27].

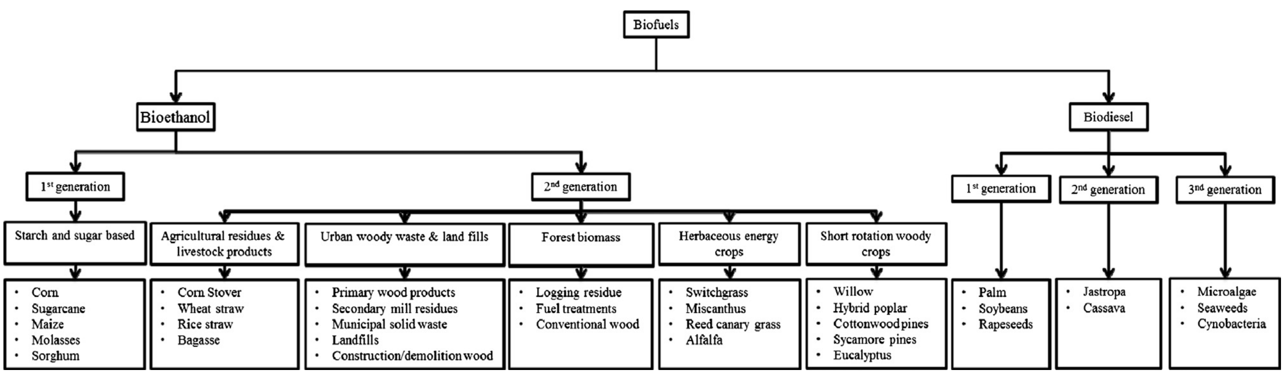


Fig. 5. Conversion processes, products, and market for biofuels/bioenergy [21].

Table 1
Lignocellulosic facilities as at February 2009 [23].

Conversion process	Pilot[a]/Demonstration[b]	Commercial[c]
Biochemical	25	9
Thermochemical	5	3

[a] Pilot scale is R&D.
[b] Demonstration scale is <10 ML/yr.
[c] Commercial scale is >10 ML/yr.

redeposition and condensation on the fiber surfaces, efficient fermentation process for conversion of C5 sugars to ethanol, cost reduction of enzyme system, and reduction of inhibitory products. The limitations with the thermochemical conversion process are the contamination by tars, and inorganic components which must be removed before the catalysis process. Technological advances in gas clean-up and preparation of catalyst are also required for large-scale implementation. The operating and set-up cost for plants using these conversion technologies is also one of the major barriers [23]. Therefore, it can be concluded that significant research advances are required in the area of conversion technology for the development of commercial-scale lignocellulosic biorefineries.

The BSC is another factor that poses technical, commercial, and strategic challenges for lignocellulosic biorefineries. Lignocellulosic biomass has significant potential for the growing ethanol industry by supplying large quantities of sustainable, less expensive, and high yielding biomass which can be produced on marginal lands, [24]. The large scale production of cellulosic ethanol will require an efficient feedstock and ethanol distribution system, production and blending facilities, and retail stations [25]. The lack of infrastructure required for on-time, cost-effective, all-year-round, and continuous delivery of large volumes of dense biomass is the major challenge [18]. It is estimated that biomass supply cost accounts for 20–35% of the total ethanol production cost, and out of the 20–35% biomass supply cost, 90% is associated with logistics [26]. Therefore, researchers are focusing on developing an integrated supply chain system design for cost-efficient delivery of biomass.

1.4. Biomass supply chain (BSC)

Supply chain is the movement of material between the source and the end-user. A typical supply chain consists of four business entities: supplier, manufacturer, distribution centers, and customers [28]. Supply chain management focuses on integration of all entities such that the end-product is “produced and distributed in the right quantity, at the right time, to the right location, providing desired quality, and service level along with minimizing the overall cost of the system” [29]. The performance of the supply chain depends on the degree of coordination and integration between the actors/entities, along with efficient flow of products and information [28].

The BSC consists of discrete processes from harvesting to the arrival of biomass at the conversion facility [30]. It essentially consists of the biomass supplier (from single or multiple locations),

the storage sites (in one or more intermediate locations), and the biorefinery sites (in one or more locations) along with pre-treatment (in one or more stages), and transportation (using one or more modes of transportation) [31]. A large number of logistical chains are possible depending on the crop and biofuel type. The complex BSC consists of two interdependent and interconnected processes: the production planning and control processes and the distribution and logistical processes. The production planning and control processes includes planting, harvesting, baling, and pre-processing/conditioning of biomass. The distribution and logistical processes consists of storage, transportation, and transshipment of biomass [32]. Fig. 6 represents a typical BSC. The "processing" refers to any operation performed on biomass to make transportation or storage easy, for example production of wood chips. The term "conditioning" refers to the process influencing specific attributes of biomass, such as decreasing moisture content [32]. The complete biofuel/bioenergy supply chain consists of additional entities such as blending sites and gas stations or demand zones. The integration of production and logistical processes of BSC is crucial for the competing biofuel/bioenergy industry.

A biorefinery requires a uniform, year-around, cost-efficient and reliable supply of desired quality biomass feedstocks. The transport, storage, and handling of biomass require careful assessment to minimize investment risk associated with a biorefinery project [33]. There are numerous sources of variability in BSC such as weather uncertainty; seasonal seasonality, physical and chemical characteristics, and geographical distribution, and low bulk density of biomass feedstocks; structure of biomass suppliers and their willingness to grow biomass crops; local transportation and distribution infrastructure; and supplier contracts and government policies. [32,34–36].

Extensive literature is available on supply chain design and management of good produced by traditional industries that are well-developed and have long history, such as automobile and consumer goods [38]. But these models could not be directly implemented to BSC. The BSC deals with the biomass supply uncertainty, biomass availability whereas the supply chain for traditional goods deals with demand uncertainty to determine economic viability of the industry. Recently, research on BSC design and modeling has focused on use of advanced software systems and tools for developing process and simulation models. The prescriptive models such as the optimization models based on linear and mixed integer programming have been used extensively in the past 50 years by the oil, and chemical industries for making strategic, operational, and tactical decisions [39]. The BSC models developed by researchers are mostly prescriptive models based on linear and mixed integer programming [40]. There are some studies that use stochastic and hybrid models for BSC analysis. The BSC models generally have an objective of minimizing costs associated with production, logistics, and operation of different sites (harvesting, storage, and conversion sites etc.) along with providing an efficient chain structure [41]. There are numerous studies focusing on the economic and technical aspects of BSC. These models help to give insight into potential future production of biofuel/bioenergy from biomass and also help in decision making at all levels of planning [42,43].

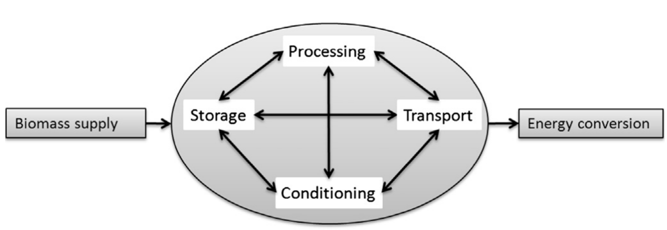


Fig. 6. Biomass supply chain [37].

2. Review methodology

One of the main objectives of this review is to provide a better understanding of mathematical modeling techniques that have been followed by researchers for BSC design and analysis. Studies on optimizing individual components of BSC were not included in the review. The review also includes studies that consider BSC with additional entities such as blending sites, distribution sites, and end-users or customers. The review does not include studies that focus on BSC simulation models. Research works which considered biomass use for bioethanol, electricity, and thermal energy production or combination of all were included in the review. This review considers articles on BSC modeling systematically published upto the year 2011.

All references related to BSC were searched using different criterion and were sorted according to their relevance to particular sections in this paper. The articles were reviewed thoroughly to present the most significant findings, which form a major part of this review. In total, 32 references were selected. Tables 2 and 3 present the distribution of references according to the journal and the year of publication. It was observed that maximum references were obtained from *Biomass and Bioenergy* (5 articles, 15.63%), and *Bioresource Technology* (4 articles, 12.50%) (Table 2). Research on developing BSC models was published in nineteen different journals. The complexity of the BSC system requires expertise from different technical area or disciplines to develop credible and

Table 2
Distribution of reviewed articles according to the journal of publication (Published upto 2011).

Journal	References	% Total
American Institute of Chemical Engineers	1	3.13
Biomass and Bioenergy	5	15.63
Bioresource Technology	4	12.50
Chemical Engineering Science	2	6.25
Computers and Chemical Engineering	1	3.13
Computers and Industrial Engineering	1	3.13
Ecological Engineering	1	3.13
Energy	2	6.25
Energy and Fuels	2	6.25
Environmental Science Technology	1	3.13
European Journal of Operational Research	1	3.13
Industrial and Engineering Chemistry Research	2	6.25
Journal of Agricultural and Resource Economics	1	3.13
Manufacturing Engineering	1	3.13
Netherlands Journal of Agricultural Science	1	3.13
Proceedings: Dynamics and Control of Process Systems	1	3.13
Process Safety and Environmental Protection	1	3.13
Review of Agricultural Economics	1	3.13
Transportation Research	3	9.38
Total	32	100.00

Table 3
Distribution of reviewed articles according to the year of publication (Published upto 2011).

Year	References	% Total
1997	2	6.25
2000	1	3.13
2003	1	3.13
2004	2	6.25
2006	1	3.13
2007	2	6.25
2008	2	6.25
2009	6	18.75
2010	2	6.25
2011	13	40.63
Total	32	100.00

realistic models. The maximum number of published articles occurred in the year 2011 (13 papers) (Table 3), which indicates a growing interest in BSC design and analysis. The specific objectives of this paper were:

- To review and classify the literature on BSC according to different classification criterion.
- To identify challenges, issues, and future research in BSC modeling, analysis and design.

2.1. Taxonomy

The taxonomy described by [44,45] was used for classification of the BSC models. An additional criterion describing entities and end-products, and assumptions and future work explicitly described in the reviewed articles was also included (Fig. 7). The classification taxonomy considered for this review is described in the following sections.

2.1.1. Decision level

A supply chain consists of a natural hierarchy of decision making processes, which include: strategic (long-term), tactical (medium-term), and operational (short-term) decisions based on their level of significance [44]. The strategic decisions focus on design of efficient supply chain with a goal of achieving organizations overall objectives and increasing its competitive advantage such as supply chain configuration (ensures effective and efficient delivery of biomass), resource allocation (ensures enough biomass is available to meet the demand of the biorefinery even under bad weather conditions), production technology selection (ensures infrastructure requirements are met and most efficient conversion technology is selected), supply and demand contracts (ensures the terms of delivery and payment between the producer and supplier are fixed), number of, location and capacity of sites (ensures economical viability of sites), and sustainability issues (ensures that social, economic, and environment impacts of building and operating a biorefinery biorefinery are addressed). The corporate strategies of a biorefinery are reflected in these decisions and they also account for sources of uncertainty in the BSC. The tactical decisions provide cost-benefit to an organization by acting within the constraints developed during strategic such as production planning and control (ensures biomass is available to meet the production plan, if excess biomass is available it ensures storage, and if biomass supply is insufficient then it ensures alternative biomass supply sources are available), inventory planning (ensures that inventory policies are in place for biomass storage) and fleet management (ensures availability, maintenance, and replacement of transportation equipment), and logistics management (ensures efficient flow of material, information, and other resources to meet end-user requirements). The operational decisions work towards fulfilling demand in a best possible way and includes detailed production, inventory, and transportation management decisions (ensures biomass is delivered in the right quantity and in time to meet the demand of the biorefinery) [34,46]. Fig. 8 presents the crucial decisions in developing efficient BSC system.

2.1.2. Supply chain structure

The supply chain structure classification described by [47] was considered in this review and is defined as the arrangement of different entities in the supply chain. The supply chain structure represents the connection between the facilities that work together to supply a product or services and structure the links in the structure are representative of the flow of information and material.

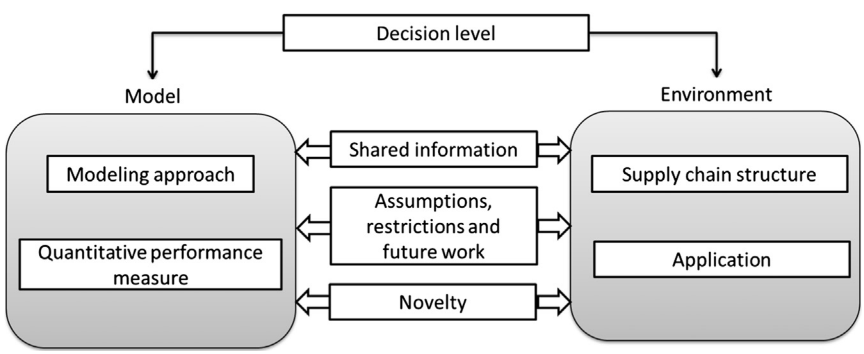


Fig. 7. Taxonomy criterion [44].

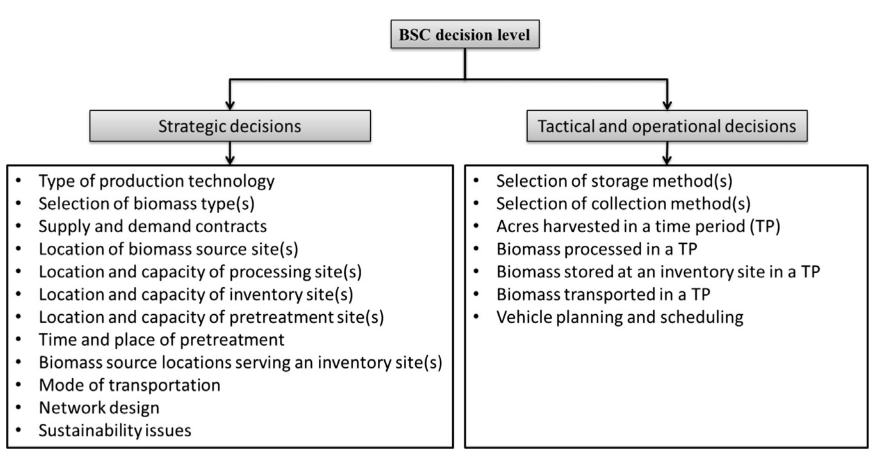


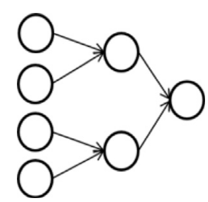
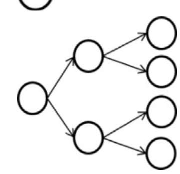
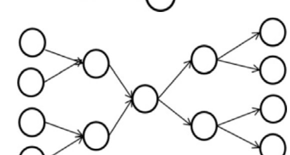
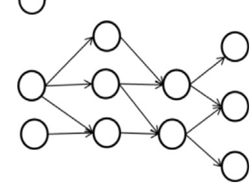
Fig. 8. Decisions related to BSC [26,32,34,46].

Convergent, divergent, conjoined, and network (general) types of supply chain structures are described in Table 4. The convergent structure is generally referred to as an assembly-like structure, where each entity has at most one successor with any number of predecessors for example, shipbuilding and airplane manufacturing industries. The divergent (arborescent) structure is the opposite of a convergent structure. Mineral processing organizations form a divergent structure. A conjoined structure is a combination of convergent and divergent structures for example web-based computers. The final structural classification consists of a network (general) structure which does not fall under any of the previously described structural supply chain classes. Examples of supply chains exhibiting a network structure are the electronics manufacturing and automobile manufacturing industries [47]. This section identifies the BSC structure considered by the authors of articles reviewed in the present study.

2.1.3. Modeling approach

Mathematical models are set of equations, which describe real world phenomena [48]. Different types of modeling approaches are used depending on the type of application. The classification of models presented by [44,45,48] were used for the present study. Fig. 9 represents the classification of modeling approaches in supply chain. The mathematical models are categorized as deterministic, stochastic, hybrid and IT-driven models. For deterministic models, the parameters are known and are fixed with certainty. They are further classified into single-objective and multiple-objective models. In stochastic models, the parameters are uncertain and random; they are also called probabilistic models. They are sub-classified into optimal control theoretic and dynamic programming models. Hybrid models have elements of both deterministic and stochastic models. The models include inventory-theoretic and simulation models. The IT-driven models integrate and coordinate various phases of supply

Table 4
Supply chain structure [47].

Classification type	Description	Example
Convergent	Each node or facility in supply chain has at most one successor but many predecessors	
Divergent	Each node in the supply chain has one predecessor but many successors	
Conjoined	Convergent and divergent structures are combined in an order and provide a single connected structure	
Network (General)	The structure which is not convergent, divergent or conjoined	

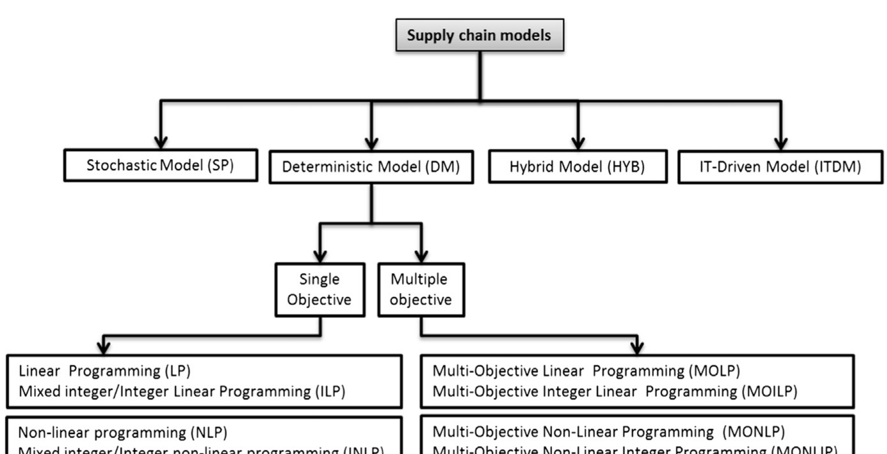


Fig. 9. Model types and codes.

chain planning on real-time basis using application software. This helps to enhance the visibility throughout the supply chain [45,48]. This section identifies modeling approach used in the articles reviewed for the present study.

2.1.4. Quantitative performance measures

One of the important components in supply chain design and analysis is the development of an appropriate performance measure for the system. These parameters measure the efficiency of a system along with comparing alternatives. The performance measures are classified into qualitative and quantitative [28]. The quantitative performance measures are expressed numerically such as cost, whereas the quantitative performance measures are conceptual such as trust. The qualitative performance measures are not generally used in BSC. Therefore, the quantitative performance measures were used to classify the reviewed articles. Fig. 10 represents the quantitative performance measures with their codes.

2.1.5. Shared information

This section identifies the shared information about the BSC related to number and type of entities, end-products, biomass type, and cost components associated with BSC. This information is crucial for efficient configuration of BSC system.

2.1.5.1. Entities, biomass types, and end-products. This section identifies the entities, types of biomass, and end-products considered in BSC models. The numbers of entities in BSC vary depending on complexity of the system considered. The entities work together to acquire biomass, convert biomass to intermediate and final products, and deliver the intermediate and final products to their users. The entities are connected through flow of material and information and each entity add value to the product. The major entities in BSC are biomass source site(s), storage site(s)/collection site(s), and processing site(s). Additional entities such as pre-processing site(s), intermediate-processing site(s), blending site(s), distribution site(s), and demand center(s) or consumer site(s) are considered in the works that evaluate the complete biofuel/bioenergy supply chain system. Pre-processing or intermediate-processing of biomass can occur at different locations in the supply chain, unless specialized equipment is required that cannot be installed at different locations. A special site is required in that case [41]. Table 5 describes the entities in the BSC structure. The end-products produced at biorefinery are bioethanol, bioelectricity, and heating and cooling system or their combination.

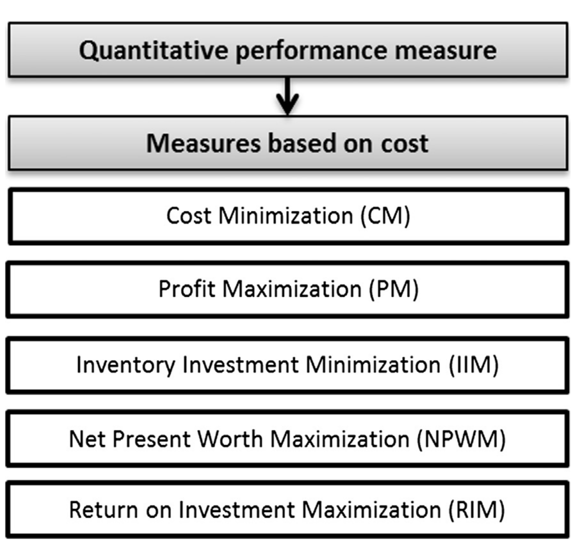


Fig. 10. Quantitative performance measures and codes.

2.1.6. Novelty

This section describes the contribution of reviewed articles to the BSC modeling design and analysis in comparison to rest of the literature. The focus is on identifying the uniqueness of modeling technique used and the major findings of the article.

2.1.7. Application

This section describes the case studies or numerical examples presented in the reviewed articles to support and present the applicability of model.

2.1.8. Assumptions, restrictions, and future work

This section identifies the assumptions, restrictions, and future work proposed by the research articles. The BSC models make some basic assumptions for developing the constraints such as land and biomass availability assumptions. The basic assumptions used for developing the constraints for the model are not identified and only the assumptions that are explicitly stated in the work are reported. The restrictions include parameters or constraints not considered in the model development. The future work consists of information provided by authors of the reviewed articles on improving their models to address additional issues related to BSC modeling.

3. Results and discussion

3.1. Decision level

The decision levels are strategic, tactical, and operational, depending on their effect in terms of time and duration [44]. The classification described in Section 2.1.1 was used to categorize the reviewed articles. Table 6 describes the BSC strategic decisions and their codes. Tables 7 and 8 classify the works reviewed in terms of strategic decisions, and tactical and operational decisions. The majority of models focused on strategic decisions related to number, location, and capacity of sites and supply chain network design. The tactical and operational decisions were related to material flow, inventory and fleet management. All reviewed models facilitate one or more decisions related to the tactical and operational planning for BSC. The reviewed articles by [49–51] assessed the environmental impact of biofuel/bioenegy production by considering GHG emissions in the model. The social impact in terms of accrued jobs was estimated by [50]. It was observed that recent studies are addressing the critical issues of sustainability and socio-economic impacts of bioenergy production. The results from the review also indicate that over the years, the mathematical models have improved in their decision making capabilities. The models are developed for the entire biofuel/bioenergy supply chain and heuristic algorithms are used to deal with the complexity of the problem.

3.2. Supply chain structure

The reviewed work was classified according to the type of supply chain structure as described in Section 2.1.2. The vast majority of the reviewed works have a network-like structure (Table 9). The structure mainly combines the biomass source sites, collection sites, and final processing sites with some works consisting of transshipment sites, pre-processing or conditioning sites, intermediate-processing sites, blending sites, and demand sites for biofuel/bioenergy. The focus is on evaluating on evaluating complex BSC designs and alternatives which results in network

like structure. Only three reviewed articles considered biomass moving to a single conversion site and thus forming a convergent structure [18,35,62]. The reason could be that these works considered a bioenergy site which was already established in the area. The already existing sites were capable of utilizing first-generation feedstocks or existing conversion technologies and had plans for upgrading to second-generation feedstock or conversion technology. Another reason for considering a convergent structure could be that the biorefinery will be or is under construction at the site. Two reviewed works evaluated a conjoined structure of BSC [2,53]. These articles considered that all biomass is transported to single biorefinery/bioenergy site and then biofuel/bioenegy is distributed to blending sites or to the end-users. The BSC does not have a divergent structure as biomass is supplied from several farms and locations to the biorefinery/bioenergy site. The supply chain structure determines the complexity of the problem and type of modeling technique used for evaluation.

3.3. Modeling approach

Table 10 presents the distribution of the reviewed works according to the modeling approach described in Section 2.1.3. The vast majority of the works reviewed followed the mixed-integer linear programming approach. The multi-objective optimization approach brings together conflicting objectives and results in Pareto optimal set of solutions and the single-objective optimization approach provides a signal optimal solution [73]. Five references followed the linear programming approach, whereas two references used the multi-objective integer linear programming approach. The advantage of mixed-integer linear models when

Table 7
Strategic decision level of the reviewed work.

Refs.	SO	PT	BT	LCPS	LCIS	LCBS	LCPPS	SPS	TM	SADC	ND	SUS
[35]					x						x	
[41]			x				x				x	
[52]		x	x	x					x	x	x	
[12]			x	x							x	
[53]			x	x	x						x	
[54]			x	x							x	
[55]			x				x			x	x	
[25]				x					x		x	
[56]			x	x							x	
[57]							x				x	
[58]			x	x							x	
[31]				x	x		x				x	
[59]		x	x								x	
[60]				x				x	x		x	x
[61]			x	x	x						x	
[26]			x	x	x			x			x	
[62]												
[63]				x							x	
[18]												
[43]				x					x		x	
[64]				x			x		x		x	
[51]	x			x							x	x
[65]				x	x						x	
[66]				x							x	
[67]	x			x	x		x				x	
[68]				x					x		x	
[49]	x			x	x				x		x	x
[50]	x			x					x		x	
[69]		x									x	
[70]				x	x		x		x		x	
[71]			x	x					x		x	
[72]				x		x					x	

Table 5
Entitiesfor biofuel/bioenegy supply chain.

Entity name	Description
Biomass Source Site(s) (BSS/BSSs)	Where biomass is harvested or acquired
Collection Site(s) (CS/CSs)	Where biomass or biofuel is collected and stored
Transshipment Site(s) (TS/TSs)	Required when using different modes of transportation
Pre-Processing or Conditioning Site (s) (PP/PPs)	Where certain operations are performed on biomass influencing its specific attributes for improving transport or storage characteristics. The processes may include pelleting, size reduction, and drying of biomass.
Final Processing Site(s) (PS/ PSs)	Where biomass is converted to biofuel/bioenergy
Additional entities	
Intermediate-Processing Site(s) (IPS/ IPSs)	Where intermediate products are produced, for example bio-oil
Blending Site(s) (BL/BLs)	Where ethanol is blended with gasoline
Distribution Sites(s) (DS/DSs)	Where the biofuel/bioenergy is collected and is distributed to final customer
Demand Center(s) or Consumer(s) (CO/COs)	Where final products such as blended gasoline, and bioelectricity are utilized

Table 6
Supply chain strategic decisions codes.

Decision	Code
Sourcing	SO
Production technology	PT
Biomass Types	BT
Location and Capacity of Processing Site(s)	LCPS
Location and Capacity of Blending Site(s)	LCBS
Location and Capacity of Inventory Site(s)	LCIS
Location and Capacity of Pretreatment Site(s)	LCPPS
Location and Capacity of Distribution Site(s)	LCDS
Sites Serving Site(s) (example biomass source site serving a particular inventory site)	SPS
Transportation Mode	TM
Supply and Demand Contracts	SADC
Network Design	ND
Ensuring Sustainability	SUS

Table 8
Tactical and operational decisions level of the reviewed work.

Ref.	Pre-treatment method	Collection method	Biomass harvested	Biomass stored	Biomass transported	Biofuel transported	Biomass processed/ biofuel/bioenergy produced	NHU*	NTU*	Others
[35]			x	x						
[41]			x	x	x					
[52]										
[12]			x	x	x		x			
[53]		x	x	x	x					Outsourcing
[54]					x					
[55]			x	x	x					
[25]			x		x					
[56]			x	x	x		x	x		
[57]			x	x	x		x		x	
[58]			x	x	x		x	x		
[31]					x					
[59]			x							
[60]			x		x	x			x	
[61]		x								
[26]			x	x	x	x	x			
[62]			x		x					
[63]			x		x	x	x			
[18]			x				x			
[43]			x		x	x	x		x	
[64]					x					IP* flow
[51]			x		x		x		x	
[65]			x	x	x		x	x		
[66]	x		x		x		x			
[67]		x			x					
[68]					x	x				
[49]	x		x	x	x	x	x			Biofuel stored, by-product produced
[50]	x		x	x	x	x	x			Biofuel and IP* stored, IP* flow
[69]			x		x					IP* flow
[70]								x		Residue produced
[71]			x	x	x		x			IP* flow and quantity processed
[72]					x	x	x			

NHU* = Number of Harvest Units, NTU* = Number of Transportation Units, IP* = Intermediate Product.

Table 9
Supply chain structure of the reviewed work.

Supply chain structure	References
Convergent	[35,62,18]
Conjoined	[61,53]
Network	[41,52,12,54,55,25,56–58,31,59,60,26,63,43,] [64,51,65–68,49,50,69,70–72]

Table 10
Modeling approach of the reviewed work.

Modeling approach	References
LP	[35,53,25,18]
MILP/ILP	[41,52,12,54–58,31,60,26,63,43,64–67,69,70]
INLP	[59,68]
MOILP	[49,50]
SP	[51,71,72]
HYB	[61]

compared to linear programming is that by means of integer variables the investment cost can be separated from the operation cost. Mixed-integer linear models are capable of making decisions related to location, technology selection, capital and investment, production planning, and inventory management. In addition, the multi-objective modeling approach provides economic, social, and environmental measures to the system [50]. However, uncertainty in BSC and computational complexities limit the decision making capabilities of these models. The uncertainty in BSC can be accounted for by using stochastic modeling techniques. Three references used the stochastic modeling approach; whereas, one reference used the hybrid modeling approach. The stochastic modeling approach handles uncertainty in the system and makes the decisions more realistic and robust. The BSC has various sources of uncertainty such as biomass supply, demand, and government incentives. The models that incorporate uncertainty factors tend to become complex and difficult to solve. Hybrid modeling approaches can handle uncertainty as well as large-size network problems. It can be concluded that the BSC uncertainties and computational complexities can be handled by using stochastic and hybrid modeling framework.

3.4. Quantitative performance measure

The performance measures used for evaluation vary among organizations and are tied to organizations strategic goals. These measures help to evaluate the effectiveness of present system and outlines areas of improvement for an organization. Table 11 presents the distribution of references according to the quantitative performance measure described in Section 2.1.4. The majority of the references used cost minimization as the quantitative performance measure. Thirteen references used profit or revenue maximization and net present worth maximization as an objective function of the work. Ref. [25] used minimization of the volume-transportation distance as a performance measure to analyze BSC. The authors claim that minimization of transportation cost was not feasible due to lack of data on fixed and variable cost for different modes of

transportation. Ref. [49] developed a multi-objective model for minimizing annualized total cost and minimizing greenhouse gas (GHG) emissions, and maximizing the number of accrued jobs. Ref. [50] proposed the same model formulation as [49] but maximizing the number of accrued jobs objective was not considered in the study. The purpose of Ref. [51] was maximizing profit and minimizing the expected economic losses under adverse conditions. The multi-objective modeling approach has potential to incorporate economic, social, and environmental impacts of BSC, but advanced techniques are required to solve complex mathematical formulations. It can be concluded that the BSC models primarily rely on traditional cost based performance measures. However, considering the complexity and uncertainty in the BSC system, in addition to cost related performance measures, non-cost based measures such as minimizing GHG emissions and maximizing number of accrued jobs should be used to provide competitive advantage to the emerging bioenergy sector.

Table 11
Quantitative performance measure of the reviewed work.

Quantitative performance measure	References
CM	[35,41,52–55,57,31,59,26,62,63,43,68,49,50,72]
PM	[60,18,64,51,65,67,70,71]
NPWM	[12,56,58,61,66]
Others	[25]—Volume-transportation distance minimization [51]—Risk minimization [49]—GHG emissions minimization and number of local jobs maximization [50]—GHG emissions minimization

3.5. Shared information

3.5.1. Entities, biomass types, and end-products

Table 12 presents the reviewed works according to the entities, biomass types, end-products as described in Section 2.1.5. The majority of the references considered multiple types of biomass feedstock for biofuel/bioenergy production. Using different types of feedstock tends to reduce overall cost of the system, but the conversion technology utilizing raw material with varying physical and chemical characteristics present major technical challenges [2]. Nine references considered heat, electricity, or combined heat and power production from biomass feedstocks. Most of these studies were done in Europe, as the three countries that form the world's most intensive cogeneration economies are in Europe. The U.S. is also aiming for 20% of energy generation capacity using cogeneration technology by 2030 [74]. These technologies are not fuel specific and thus help in developing a balanced and sustainable energy portfolio [75]. The two entities considered by majority of references were the biomass source and conversion sites. Some of the studies focused on an integrated view of biofuel/bioenergy supply chain by considering all the entities from biomass source sites to end-user/demand centers. An integrated approach of evaluating bioenergy/biofuel supply chain is necessary as the components of this system highly interconnected and interdependent [76]. The upstream decisions are associated with biomass production, biomass delivery, and conversion sites while, the downstream decisions are associated with biofuel/bioenergy distribution to the end-user/demand centers. The upstream decisions have significant impact on the later activities in the supply chain [51,76]. Therefore, it is important to consider all entities of the biofuel/bioenergy supply chain system in its design and analysis.

This section also considers information about costs, biomass availability, and production capacities for the reviewed articles.

Table 12
Entities, biomass types, and end-products of the reviewed work.

Ref.	Biomass type	End-product	Entities
[35]	Switchgrass	Bioethanol	BSSs, CSs, PS
[41]	Multiple biomass types	Biofuel	BSSs, CSs, PPs, PSs
[52]	Wood, straw, biogas, rapeseed	Heat or power or co-generation	BSSs, PSs , DSs, COs
[12]	Multiple biomass types	Bioethanol	BSSs, PSs
[53]	Cotton-plant stalks	Combined heat and power	BSSs, CSs, PSs
[54]	Forest biomass	Thermal and electric energy	BSSs, PSs, DPs
[55]	Forest residue	Heating plants	BSSs, CSs, PSs
[25]	Switchgrass and corn	Bioethanol	PSs, DPs
[56]	Multiple biomass types	Bioethanol	BSSs, PSs
[57]	Miscanthus	Heat	BSSs, CSs, CPPs, PS
[58]	Multiple biomass types	Bioethanol	BSSs, PSs
[31]	Waste biomass	Bioenergy	BSSs, CSs, PPs , PSs
[59]	Forest biomass	Thermal energy and electricity	BSSs, CSs, PSs
[60]	Multiple biomass types	Bioethanol	BSSs, PSs, DPs
[61]	Multiple biomass types	Electricity, heating and cooling	BSSs, CSs, PSs, DPs
[26]	Multiple biomass types	Bioethanol	BSSs, CSs, PSs, BLs
[62]	Mallee	Bioenergy	BSSs, PSs
[63]	Multiple biomass types	Bioethanol	BSSs, PSs, DPs
[18]	Multiple biomass types	Heat, power, and biofuel or all	BSSs, PSs
[43]	Multiple biomass types	Bioethanol	BSSs, PSs, DPs
[64]	Multiple type biomass	Gasoline and biodiesel	BSSs, PSs, IPSs, DPs
[51]	Corn	Bioethanol	BSSs, PSs, BLs, DPs
[65]	Switchgrass	Bioethanol	BSSs, CSs, PSs
[66]	Agricultural residues	Bioethanol	BSSs, CSs, PSs
[67]	Multiple biomass types	Bioethanol/Biofuel	BSSs, CSs, PPs, PSs, DSs, DPs
[68]	Biomass	Bioethanol	BSSs, PSs, DPs
[49]	Agricultural residue, energy crops and wood residues	Bioethanol	BSSs, CSs, PSs, DPs
[50]	Cellulosic biomass	Gasoline and biodiesel	BSSs, IPSs, PSs, DPs
[69]	Multiple biomass types	Biofuel	BSSs, CSs, IPSs, PSs, DPs
[70]	Perennial grasses and agricultural residue	Bioethanol	BSSs, CSs, PPs
[71]	Multiple biomass types	Gasoline and biodiesel	BSSs, PSs, IPSs, DPs
[72]	Bio-waste	Bioethanol	BSSs, PSs, BL/BLs, DPs

Table 13
Shared information on cost of BSC for the reviewed work.

References	*BC	*PTC	*CC	*TC	*IC	*PC	*O
[35]	x			x	x		Construction/expansion of storage facility, penalty cost for demand shortage
[41]	x	x	x	x			
[52]				x		x	Capital and operating cost of facility, fuel costs, disposal costs for waste-products, distribution cost
[12]	x			x	x	x	Capital and operating cost of facility
[53]	x	x		x	x	x	Capital cost of facility
[54]	x			x		x	Capital cost of facility, energy distribution cost
[55]	x	x	x	x	x		
[25]	x			x			
[56]	x			x	x	x	Capital and operating cost of facility, cost of harvest units
[57]	x	x		x	x	x	
[58]	x			x	x	x	Capital and operating cost of facility, cost of harvest units
[31]	x			x			Capital and operating cost of facility
[59]	x			x			Capital and operating cost of facility
[60]				x			Capital cost of facility
[61]	x		x	x	x	x	
[26]	x			x	x	x	
[62]	x		x	x			
[63]	x			x		x	Capital cost of facility, penalty cost for demand shortage, loading and unloading cost
[18]						x	
[43]	x			x		x	Capital cost of facility
[64]	x			x			Capital and operating cost of facility
[51]	x			x		x	Capital and operating cost of facility
[65]	x		x	x	x		Cost of owning and operating harvest unit, capital cost of facility, handling residue cost
[66]	x	x	x	x			Capital and operating cost of facility
[67]	x			x	x		Capital cost of facility
[68]				x			Capital cost of facility
[49]		x		x	x	x	Capital and operating cost of facility
[50]	x			x	x	x	Capital and operating cost of facility, distribution cost
[69]				x			Capital and operating cost of facility
[70]	x			x	x	x	Capital and operating cost of facility
[71]	x			x			Capital and operating cost of facility
[72]	x			x		x	Capital and operating cost of facility, penalty cost for demand shortage

* BC—Biomass cost, PTC—Pre-treatment cost, CC—Collection/handling cost, TC—Transportation cost, IC—Inventory cost, PC—Processing cost, O—Others.

The majority of references shared information on biomass availability, production capacities, and production rates. The cost information shared by the references is presented in Table 13. The vast majority of works reviewed provided biomass cost, processing cost, and transportation cost. Depending on the entities considered by the model, the additional cost elements were added. Three references also included the penalty cost for not meeting demand. Adding penalty cost forces the model to meet the demand of biomass. But, in a real world situation there will be scenarios when the demand could not be met due to uncertainties in weather or biomass supply. The constraints considered by the models were also evaluated. Demand, flow balance, capacity, and logical constraints were the most common types for the BSC modeling system. Three references included constraints for ensuring sustainability by limiting the use of biomass to prevent negative impact on food production [43,51,59]. Ensuring sustainability in BSC is critical for the long-term successful operations of biorefineries. Ref. [61] includes a social constraint for safe distance of the conversion plant from demand sites. The constraints addressing environmental impacts and social benefits in BSC modeling helps to assess impacts of biofuel/bioenergy production at regional and local level.

3.6. Novelty

Table 14 describes the novelty and contribution of the reviewed work to existing BSC models. It was observed that modeling techniques and solution capabilities have improved significantly over the years. The mathematical models have been developed with capabilities to consider several parameters and variables along with addressing economic, environmental, and social benefits. Majority of the models developed for evaluating BSC were Mixed-Integer Linear Programming Models (MILP). Considering the complexity of BSC and the large number of alternatives that can be analyzed, MILP models pose computational limitations. In addition, the models do not consider the dynamic nature of the system but emphasize on developing models considering process and environment variability for better planning [42,49,50,54,61,63,67]. Therefore, recent research has focused on developing models that can deal with large-scale optimization and, uncertainty in the system. Ref. [69] proposed model size reduction techniques to improve computational time without loss of accuracy in large-scale linear models for BSC. Some of the models developed in BSC consider uncertainty in demand and price by formulating different scenarios [43,51,60]. Ref. [49,50] provides comprehensive view of the BSC by considering economic, environmental, and social aspects of the BSC system. But the authors emphasized on investigating uncertainty in ethanol demand fluctuations, biomass supply, and government incentives in the models as the future work. Majority of the articles reviewed developed generic optimization models while some of the authors introduced different modeling framework task-network [57], spatially explicit [60], multi-stage [22], multi-echelon [51], time-staged multi-commodity [67], multi-objective/multi-period [49,50] two-stage linear programming [35], two-level facility location problem [55], and two stage SP [72] models. The new approaches for modeling BSC contributed by providing increased decision making capabilities and addressing some of the critical issues of BSC. However, techniques such as scenario optimization and simulation optimization can address additional issues related to uncertainty and computational complexity of the bioenergy system.

3.7. Application

Table 15 presents the practical application or numerical examples and major findings of the reviewed works. In addition this section also provides an outline for the scale and validation of the

Table 14
Novelty of the reviewed work.

Ref.	Novelty
[35]	A two-stage linear programming model with recourse was developed. Uncertainty in biomass yield during growing and harvesting seasons was addressed by considering four weather scenarios. The model provides realistic cost estimates for biomass delivery to biorefinery.
[41]	A network structure model solved by integrating the three sub-models (biomass flows without pre-treatment, biomass flows with pre-treatment in a separate pre-treatment site, biomass flow with pre-treatment possible in every node) into a Knapsack model. A comparison was made between the optimization model and simulation model. It was concluded that both optimization and simulation models provide insight into the costs of biomass supply. The optimization model resulted in best network structure, and the simulation model provides more insight into costs involved.
[52]	An integrated optimization model for energy production considering three types of operating companies was developed. The model considered three dimensions: technology, location, and time. The model provides a comprehensive scenario analysis with a base scenario consisting of price of fuels, reduction of heat consumption, CO_2 emissions, investment cost, and central and individual conversion plants. The model can simulate the political, economical, ecological circumstances or future goals, by making changes to the base scenario.
[12]	A comprehensive multi-region, multi-period integrated model was developed. The model considered biomass harvest window, field losses, storage losses, fertility regime, and multiple output products.
[53]	An integrated planning model was developed. The model analyzed centralized and decentralized structure for CHP-cogeneration along with considering two scenarios for collection and transportation: third party companies and the farmers undertake these tasks. Different power plant capacity scenarios were also considered. The model has potential for developing future business strategies for biomass.
[54]	A Decision Support System (DSS) for forest biomass, combing the Geographical Information System (GIS) techniques along with mathematical programming and database was developed. The DSS system can be used for biomass exploitation in a region, determining the location and capacity of plants, and evaluation of overall performance of the system. The system considers the biomass areas ensuring sustainability.
[55]	A two-level facility location problem was modeled and solved using heuristics approach based on sequential LP. The harvest areas considered were self-owned or contracted. The model can be used for better planning and testing of different alternative scenarios. The model can analyze strategic planning situations such as a company competing for a new contract and wants to submit the contract prices, and the company wants to conduct sensitivity analysis on variation in the demand.
[25]	A minimization transportation-distance optimization model was developed considering economic costs of distribution of different ethanol blends to all metropolitan areas in the U.S. It was concluded that an efficient transportation system and processing technology is required to make ethanol use feasible and competitive in the long-run.
[56]	The model is an extension of the model developed by Ref. [12]. The total number of harvest units was estimated. The model considered restrictions in harvest schedule due to harvest season length and frequency of harvest on CRP land. The model provides insights into how the policies that restrict the harvest season length and frequency of harvest can affect the cost of biomass supply to the biorefinery.
[57]	A state-task-network approach was presented for design and scheduling operations for biomass to heat supply chain. To demonstrate the effectives of the approach the optimal designs from the model were compared to those derived from heuristics based strategies. It was concluded that potential economic benefits can be achieved by applying system optimization methods. The results showed that 5–25% improvements in cost minimization objective can be achieved.
[58]	The model was an extension of model developed by Ref. [12]. The model incorporates number of harvest days per month based on the historical weather patterns. The storage losses were associated with location and time of storage. The results from previously developed model were compared to the present model. The assumptions made for the harvest units affect the results from the models. The present model provides more realistic and reliable estimates on harvest costs by considering number of workdays in comparison with the previously developed models which considered harvest cost as fixed cost per mg of biomass harvested.
[31]	A quantitative model was developed for making strategic decisions of identifying nodes for different operations of BSC and determining the biomass flow in the network.
[59]	Environmental DSS consisting of GIS interface, database and optimization module was developed. A user-friendly interface allows developing and running scenarios for strategic planning.
[60]	The spatially explicit model was developed considering economic and environmental impact of BSC system.
[61]	A DSS with hybrid optimization method was developed. The demand driven system-wide optimization was done. The model provides practical tool for investors to evaluate and optimize system to achieve cost-effectiveness with incorporating the real energy demand.
[26]	A network design problem capable of making strategic, tactical and operational decisions was developed. The model minimizes system wide cost.
[62]	A discrete mathematical model was developed for Mallee biomass. The model considers differences between the on-farm transport and road-transport along with considering tortuosity of roads.
[63]	A mathematical model which integrates the spatial and temporal dimensions was developed. The authors states that optimizing entire supply chain provides better understanding of tradeoffs between the spatial and temporal dimensions.
[18]	A generic optimization model for biomass conversion to heat, power or biofuel production was developed.
[43]	An optimization model using 4N and 8 N neighborhood representation modeling approach was developed. The model can solve large-scale network problems.
[64]	An optimization model considering pyrolysis process and Fischer Tropsch process for forest biomass conversion was developed. The model compares the centralized and decentralized network structure with regard to profit per ton for different demand scenarios. The model can contribute to the development of process system design for organizations other than the biofuel industry.
[51]	A dynamic, spatially explicit, and multi-echelon model was developed. The model had two objective functions of maximizing profit and minimizing losses under adverse conditions. The model consisted of scenarios for corn cost and selling price of ethanol. The model provides network structure with regard to biomass source sites, production sites, and transportation logistics.
[65]	A model was developed for strategic and tactical level planning for switchgrass supply chain. The model considered switchgrass harvesting and non-harvesting seasons. The authors claim that a well-designed logistics system results in increase in the unit profit from bioenergy production.
[66]	The model was developed for 9-state region in the Midwestern U.S. and concluded that the region has the capacity to run a 4.7 BGY cellulosic ethanol plant.
[67]	A time staged multi-commodity model was developed. The model provides compressive view of both upstream and downstream echelons in BSC. The model can be used by the manufactures to determine the most profitable scenario and can be used by the Government policy makers to determine the policies that are effective for successful implementation of biofuel industry.
[68]	The model is an integration of a traffic assignment model and a fixed-charge facility location problem. The model explicitly incorporates shipment routing decisions and traffic congestion impact into facility location design model to determine biorefinery location and transportation of ethanol. The model was solved using Lagrangian relaxation (LR), linear programming relaxation, branch and bound, and convex combination approaches. The LR approach solved the model in less time and resulted in good feasible solutions.
[49]	A life-cycle analysis technique was integrated with multi-objective and multi-period optimization model to evaluate alternatives to achieve economic, environmental, and social improvement. The problem was formulated as bi criteria optimization model and solved with e-constraint method. The model considers seasonality of biomass feedstock, biomass loss with time, geographical diversity, biomass variability, feedstock density, moisture content, conversion technologies and byproducts, infrastructure, demand distribution, tax subsidies, policies, and regional economic conditions. Biochemical and thermochemical pathways were considered for conversion.
[50]	The life-cycle analysis technique was integrated with multi-objective, multi-period mathematical model with economic and environmental objective functions. The emissions during all stages from “field-to-wheel” were considered. The model considers seasonality of biomass feedstock, biomass loss with time, geographical diversity, biomass variability, moisture content, conversion pathways, infrastructure, and demand variation. The multi-objective model resulted in Pareto-optimal curve. The curve presented the variation in the optimal annualized cost and the biomass to liquid processing network change with different environmental performances.
[69]	An optimization model considering 4 layers supply chain structure was developed. Different techniques such as reducing connectivity in the

Table 14 (*continued*)

Ref.	Novelty
	network, removing unnecessary variables and constraints from the zero-flows, and merging of zones within the network was used for model size reduction. It was found that these techniques reduce computational time significantly with little loss in accuracy.
[70]	A multi-commodity network flow model was developed.
[71]	A two-stage mixed integer stochastic model was developed. A methodology consisting of sequence of steps was proposed to deal with uncertainty in parameters. First, the single nominal scenario was optimized and then the value of objective function for extreme values of 14 major parameters was analyzed. Finally, the high impact parameters were selected and multiple scenarios were generated and analyzed for optimal design. Robustness analysis and global sensitivity analysis were done for the comparison of nominal design vs. scenario design. The methodology was successful in dealing with parameter variation and uncertainty.
[72]	A two stage SP model was developed. The feedstock supply and demand uncertainty was dealt by considering set of possible scenarios. The SP modeling increased the computational burden and could not be solved using commercial software. Decomposition methods reduced the problem size and tend to provide realistic estimates on cost and network design. It was concluded that advanced system based approaches can provide better design and analysis of BSC system.

models developed by researchers. The majority of the works presented a case study for a region, with some studies assuming the data and others using realistic data sets. The extensive use of case studies to validate the model shows that the models developed have practical applicability when used with regional or local constraints.

3.8. *Assumptions, restrictions, and future work*

Table 16 presents assumptions, restrictions, and future work for the reviewed articles. This section provides directions for future research in the BSC design and analysis. The assumptions that were explicitly stated in the work were reported. Majority of the reviewed articles assumed that lignocellulosic biomass is available for biofuel/bioenergy production and that it is technically feasible to convert biomass to biofuel/bioenergy. Additional assumptions made for developing models were dependent on supply chain structure, number of entities, and modeling techniques used in that particular model. While sophisticated modeling approaches are increasingly used, still model applicability is limited to a range conditions. The restrictions specific to a particular model depending on the modeling technique used and complexity of the BSC considered were identified. The future work identified primarily focus on developing models to handle large-scale problems and addressing different sources of uncertainty such as demand fluctuations, biomass supply disruption, and changes in government policies and incentives in the BSC models.

4. Issues, challenges and future direction

Although the numerous benefits of using biomass for biofuel/bioenergy are evident in terms of their potential to provide energy security, rural development, and GHG mitigation, the conversion technologies and supply logistics pose serious challenge for their commercialization [25]. The BSC is a complex system with interconnected upstream and downstream supply chain decisions. Decisions affect the activities in the supply chain later [76]. The optimization models help to evaluate the feasibility of biomass use for biofuel/bioenergy and support decision making at various levels. Most of the studies reviewed focused on location/allocation of biomass/biorefinery, inventory management and control, and production planning. With commonly used quantitative performance measures of cost minimization or profit maximization. The configuration of BSC is challenging due to the large number of factors affecting the system. The modeling complexity increases significantly while designing such a system. The modeling technique should consider all the factors to provide realistic solutions (Fig. 11) [2,32,33,36].

4.1. *Modeling technique and computational complexity*

The mixed-integer linear programming models (MILP) developed for BSC are capable of making strategic, tactical and operational decisions. But, the uncertainty in BSC is not addressed by the MILP models. Uncertainty exists when there are chances that results will deviate from the expected. The existence of uncertainty is associated with risk [78]. In supply chain design, uncertainty is the major factor that influences effectiveness of configuration and coordination of the system [79]. The uncertainty propagates in the spatial and temporal dimensions of BSC, thus significantly affecting the performance of the system. Considering uncertainty in BSC modeling is one of the major challenges faced by researchers. The uncertainties in BSC are due to the following factors:

- Biomass supply
- Weather
- Biomass properties such as moisture content
- Biomass cost
- Technology
- Expansion plans
- Demand fluctuations
- Biofuel price
- Change of Government incentives
- Change of regulations and policies
- Natural or human disasters

As uncertainty forms a major portion of the problems associated with BSC modeling, a different modeling strategy is required. Under uncertainty, the values of parameters vary according to the nature of uncertain factors. This results in possible scenarios for the parameters [78]. The commonly used approach to deal with uncertainty is analyzing present scenarios separately. This technique is called the “Wait-and-see” approach, as one has to wait and see the actual random event and make decisions according to that situation [72]. This technique is appropriate if one scenario is analyzed, but with several realizations or scenarios for the parameters, this technique is not appropriate. Three additional techniques to deal with uncertainty are:

- Scenario optimization
- Robust optimization
- Simulation optimization

Scenario optimization and robust optimization are the traditional methods to deal with uncertainty. They are effective in finding feasible solution for all scenarios under consideration. However, these techniques are limited to of handle small sets of scenarios, and the size and complexity of problem that they can handle is also limited [78]. Therefore, these modeling approaches might not be appropriate for the BSC with large numbers of scenarios to be analyzed with large amounts of data.

In addition, the BSC models need to be adapted to large geographical area (to develop national level case studies), weekly or daily time periods in the planning horizon (to account for the variable biomass properties such as moisture content), longer planning horizons (to account for the productive life of biomass crops such as switchgrass which has a 3 year establishment period

Table 15
Application and important findings of the reviewed work.

Ref.	Application and important findings
[35]	A case study for a hypothetical bioethanol plant located in the Piedmont county was presented. 20 switchgrass producers with each producer having 4 to 7 storage location were considered. Switchgrass from 3 to 10 fields was stored at each storage location. Cost estimates for switchgrass delivery were estimated along with recommendation of shipping and capacity expansion schedules for each producer.
[41]	A case study for province of North-Holland in Netherlands was developed. Biomass types: thinning and restwood, pruning, waste wood, sewage sludge, and waste paper; Transport modes: road, rail or water transport; Pre-treatment of biomass: particle size reduction and drying; Location of energy plant: 4 possible locations. Authors concluded that centrally located energy plant was economical. Road and water transportation modes were found desirable and pre-processing should be done at the energy plant.
[52]	A practical application of model to a rural municipality of the Brandenburg area was developed. The author concluded that production and supply of bioenergy is possible and in addition, use of biomass feedstock reduces CO_2 emissions upto 25% in comparison to fossil fuels.
[12]	A case study for 77 counties with 11 potential biorefinery locations for the state of Oklahoma was developed. 8 alternative scenarios to determine a breakeven price of ethanol were evaluated: doubling land cost, doubling biorefinery investments cost, doubling per mile feedstock transportation cost, changing project life to 10 years, changing project life to 20 years, and using discount rate of 5% and 25%. The base scenario results showed development of 5 large biorefineries (100 million gallons/year) and 1 medium sized biorefinery (50 million gallons/year) in Oklahoma. The breakeven price of ethanol was found to be approximately $0.758/gallon.
[53]	A case study for Thessaly with almost 30,000 cotton producers, the biggest cotton harvesting area of Greece and Europe was developed. The results indicate that the most economical method for transporting biomass requires farmer's involvement in the logistics system. It was also observed that the economies of scale can be achieved with increasing capacity of transportation vehicles. The warehousing method suggested was closed depots and drying, and was found to be more cost-effective than baling.
[54]	A case study for Val Bormida, Savona district, Italy was developed. The area was divided into 370 parcels containing 1 of the 4 main types of biomass (beech, oak, chestnut, and conifer) and the biomass waste from 10 industrial sites was also considered. The results showed that 16% of the energy demand can be satisfied at a reasonable cost with the available biomass. The results also indicate that bioenergy production fulfills local thermal and energy demands and electric energy was only produced during low energy demand at any plant.
[55]	A case study for Swedish entrepreneur of Sydved Energileveranser AB was developed. Sydved is the largest supplier of biofuel energy in Sweden. The case study was developed for the north region of company consisting of Värmland, Närke, Södermanland, Stockholm, Uppland and Västmanland counties. Different scenarios were developed considering increased demand, restriction on storage levels, more customers, changing chipping capacity, and adding new terminals. It was found that the by-products should be stored at the terminals and once the forest biomass is chipped, it should be directly transported to the heating plant. The results could not be compared to the manual solutions. The authors suggest that the manual solutions work fine at the beginning of the year but towards end of the year, these solutions are not valid and become problematic.
[25]	A case study for the metropolitan areas in the U.S. was developed. The shipments of corn and cellulosic ethanol blends (E5, E10, and E16) to 271 largest Metropolitan Statistical Areas (MSA) was considered. Different scenarios ethanol blends and ethanol and switchgrass yields were studied. It was concluded that pipelines are the most effective method for shipping ethanol. Increased use of ethanol can have positive impact on energy security, economy, and environment. But the total infrastructure required for such changes is challenging.
[56]	A case study for the 52 Kansas counties, 77 Oklahoma counties and 32 Texas counties considering perennial grasses including prairie grasses established on CRP acres in these regions was developed. Results showed that 11 counties were considered as potential biorefinery locations sites. The model was executed for 9 different scenarios considering different policies of harvest days, frequency of harvest, and biorefinery size. It was found that restriction on harvest days and frequency of harvest increases the harvest, storage, and transportation costs. The increase in biorefinery size resulted in an increase in the number of harvest units required.
[57]	The model was tested for a hypothetical heat plant with 20 MWth peak output using surrounding agricultural resources within approximately 1225 square km area. 2 Distant spatial locations were considered: a farm which consists of cultivation, harvesting, storage, decentralized drying, and chopping process, and a centralized conversion plant included storage, centralized chipping, forced drying, and combustion processes. The results indicate that land, cultivation, and harvesting cost account for the major portion of supply chain economics.
[58]	The same case study as presented by [12] was considered. 26 Harvest units were found to meet the demand of biorefinery. Whereas, the conventional model resulted in requirement of 55 harvest units. It was concluded that associating harvest capacity with number of harvest days available in a month provides realistic cost estimates.
[31]	A case study for wood industry located within the region of central Macedonia, Greece was developed. 3 echelons were considered for the study with 7 collection points, 2 potential storage nodes, and 1 final destination. Wood based particle boards and wheat straw were the biomass resources. Results indicate that biomass should be directly transported to plant.
[59]	A case study for Val Bormida Province consisting of 2,300 parcels was considered. The biomass plant location was at the Cairo Montenotte district. It was found that fast pyrolysis and diesel engine technology plants have fewer benefits compared to other technologies. The fluid bed gasification received the worst economic value. The grate firing combustor and steam cycle technology required less supervision and could be easily managed.
[60]	A case study was developed for corn-based ethanol production in the northern Italy. 4 Ethanol plants of varying capacities at Venice Harbor, Porto Viro, Tortona, and Trieste were considered. The Venice Harbor and Porto Viro facilities were under construction and assumed to start production first. Two demand scenarios with 3% penetration by energy content for the year 2009 and 5.75% penetration by energy content for the year 2010 were considered. The results indicate that to meet the 2009 demand, the ethanol plants of 120,000 and 150,000 tons/year capacity should be located at Venice and Milan, respectively. For the 2010 scenario, it was suggested that additional capacity of 240,000 tons/year for Venice plant and construction of a same capacity plant at Milan. The cost saving was found to be of 8% in comparison with the likely planned scenarios.
[61]	A case study for the district of Thessaly, Greece with 5 biomass types (wheat straw, corn stalks, cotton stalks, olive tree pruning, and almond tree pruning) was considered. The real biomass availability data was used to locate a multi -biomass conversion facility. The results showed that inexpensive biomass type with low moisture content was selected for bioenergy production. The transportation cost was low as the result of high biomass availability and small size of plant. Some biomass types were transported over long distances to reduce the inventory cost. The interest rate had highest impact on project cost followed by investment cost and operational and maintenance cost. Biomass cost had little effect on Net Present Value (NPV) as it was cheap and readily available. The case study provides investors with detailed analysis and optimum design of BSC.
[26]	A case study for corn stover and woody biomass (forest residue, pulpwood, and saw timber) for Mississippi was developed. 45 to 84 counties were considered depending on the corn availability in each county. It was found that small size biorefineries are economical if biomass availability is low and transportation costs are high, and developing 2–3 small size biorefineries will decrease overall cost rather than having one central biorefinery. The improvement in conversion technology can have significant impact on the costs associated with biofuel production.
[62]	A case study for mallee biomass production in the "wheat belt" of Western Australia was developed. It was found that on-farm haulage and road transport makes significant contribution to the total cost. The on-farm haulage was more expensive than the road transport for the same distance traveled. The long distance biomass road transport was not feasible. The strategies suggested by the authors to reduce delivery cost of a mallee are: location of biorefinery sites close to feedstock availability, managing the on-farm tracks so that the road trailers can be near to the harvester, and to incorporate the biomass transportation into the growers or biorefinery business rather than using the services from various independent third parties.
[63]	A case study for 8 waste biomass resources (corn stover, rice straw, wheat straw, forest residue, municipal solid waste wood (MSW), MSW paper, MSW yard, and cotton residues) for California was developed. 29 Potential biorefinery sites were considered. MSW yard and paper were identified as primary feedstocks. The cost of ethanol was estimated around $1.1/gallon for efficient BSC.
[18]	A case study for the area of Thessaloniki, Greece considering multiple biomass types was developed. It was found that expensive biomass types should not be used for energy production.

Table 15 (*continued*)

Ref.	Application and important findings
[43]	The case study developed by [60] with two demand scenarios for the year 2011 and 2020 based on the EU biofuels targets was considered. The local and global sustainability constraints were applied to both scenarios. Local sustainability resulted in higher overall cost for the supply chain as compared to global sustainability mainly due to increase in biomass transportation cost.
[64]	A case study was developed for the southeastern part of the U.S. using realistic data set. Region of study includes 10 states (Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Georgia, Florida, South Carolina, and North Carolina), 30 biomass source locations, and 29 possible locations for conversion plant 1 where intermediate product is produced (bio-oil, char and fuel gas), and 10 possible locations for conversion plant II where bio-oil will be converted to biodiesel and gasoline. A distributed supply chain system was compared with the centralized system. The scenarios evaluated by reducing the demand by certain percentage to represent market fluctuations. The results showed that the input parameters affect the overall economics, and distributed system was economical and robust to demand variations.
[51]	A case study for northern Italy considering different transportation modes (trucks, rail, barges, and ships) was developed. Trans-shipping was included as a feasible option. The scenarios were developed for the fuel price and corn cost. Two separate cases were analyzed: planning under profit maximization and risk minimization. The profit maximization case indicated that there is probability of getting profit if it is assumed that DDGS processes will decrease over the years. The risk minimization case indicated that high DDGS selling price might lead to profit otherwise the company should not invest in the ethanol production. It was also found that building a production plant near the coast will increase the opportunity for corn import.
[65]	A numerical example with 10 switchgrass production fields, 3 potential intermediate warehouse locations, and 2 potential biorefinery locations was developed. The results indicate that logistics cost estimates were different for the harvesting and non-harvesting season, truck as well as train transportation modes are feasible, and owning a transportation fleet by the biorefinery will increase the cost significantly and is not recommended.
[66]	A case study for 9 state regions for the Midwest U.S. (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, South Dakota, and Wisconsin) with residues of barley, corn, and oats, spring wheat and winter wheat as biomass feedstock was considered. The base model consisted of 69 potential biorefinery locations with 4 biorefinery capacities, 187,595 decision variables, 276 binary variables and 5557 constraints. The results indicate that biorefineries can be located in 65 of the 69 potential biorefinery locations. The total estimated capacity of the system was 4.7 billion gallons. The authors concluded that there is 21.5% chance that the biofuel industry will not develop, and if it develops it will be uneconomical for about 15% of the time.
[67]	A case study of 9 counties in central Texas with switchgrass as the biomass feedstock was developed. 21 Scenarios were analyzed. Results indicate that the local demand for ethanol can be met by using E10 blend. Ethanol price was considered as the most important factor for economic viability of biomass and biofuel supply chain.
[68]	The model was applied to 12 node networks from the Daskin, Sioux-Falls network, and the Anahim network. A case study for the state of Illinois was developed. The transportation network consisted of 98 nodes and 374 links. It was assumed that 102 counties in Illinois produce 45% of national ethanol demand. The benchmark design (without congestion) and design with congestion considered were compared. It was observed that with congestion considered, the impact of biofuel traffic to the general public was low.
[49]	A 2 county level case study for state of Illinois was developed. 3 Biomass types, each of 102 harvesting sites, potential collection sites, potential biorefinery sites, and demand zones were considered. Two scenarios were evaluated: the near-term scenario (10% of fuel usage of Illinois met from cellulosic ethanol), and year 2022 scenario (16 billion gallon of cellulosic ethanol produced/consumed in Illinois). The results from both scenarios indicate that biorefinery plants are located in the regions with high biomass density and close to the major demand centers such as the Chicago area. It was observed that 70% of the total cost of the BSC is the capital investment and production cost, and conversion technology is the major barrier in the commercialization of biofuels.
[50]	Two case studies were developed. The first case study illustrates the trade-offs between centralized, distributed, and distributed-centralized biomass to liquid (BTL) processing network design, and the second case study was for the state of Iowa. First case study considered, 16 square farms in a 4×4 array with 5 potential facility locations. Centralized design was found to be the best option due to economy of scale and integrated conversion. The distributed-centralized design was also considered a feasible option with slightly higher capital cost. The second case study was for each of 99 potential integrated biorefinery locations, potential pre-conversion locations, potential upgrading facilities, and demand zones for the state of Iowa. The feedstocks considered were crop residue, energy crops, and wood residue. Pareto curve was obtained using bicriterion optimization. It was observed that 14, 11, and 17% of the total cost for BTL supply chain was associated with capital investment, fixed operation and maintenance, and variable production cost, respectively. The feedstock procurement and transportation accounts for 25%, storage contributes 7%, and conversion efficiency and equipment utilization accounts for 43% of the total cost. It was concluded that major barrier in the development of efficient BTL system is the technological barriers associated with conversion process.
[69]	A case study developed by [77] was extended and evaluated for the study. The type of plantation and number of zones were increased. Solution times for different problem size reduction techniques were compared. Combination of techniques such as reducing connectivity in network, merging of zones within network, and regional development planning has potential for evaluating large-scale problems.
[70]	A numerical example developed by [65] with additional 2 corn stalk and 2 wheat straw fields was evaluated. Scenario-1: switchgrass as the only feedstock, Scenario-2: multiple types of feedstocks, Scenario-3: three configurations with decreased yield, increased yield, and mandatory provision for switchgrass were considered. Scenario-1: 28 harvest units were required, the biorefinery production drops during non-harvesting season. Scenario-2: biofuel production increased significantly and using multiple types of feedstocks increase profit and provide continuous production throughout year.
[71]	A case study for a thermo-chemical conversion biorefinery for the southeastern part of the U.S. was considered. Realistic cost estimates were used for analysis. The region of study comprised of 10 states (Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Georgia, Florida, South Carolina, and North Carolina), 5 biomass types, 30 biomass source locations, 29 possible intermediate conversion plant 1 locations, 10 possible conversion plants II locations (bio-oil is converted biofuel), and 10 demand points. A single nominal scenario and multiples scenarios were compared. It was concluded that multiple scenario design decreases the impact of variation and retains all major components of profit variation.
[72]	A practical application for the state of California to evaluate the bio-waste ethanol production was developed. 8 bio-wastes types, 28 potential refinery sites, 29 potential terminal sites, and 143 demand clusters were considered. A comparison of results for 4 possible demand scenarios was done using a stochastic model (SM) and deterministic model (DM). Low cost estimates were obtained using SM as compared to DM. The SM solutions were reliable and resulted in small range of total costs. The implementation of the model for a large-scale real world problem was feasible. The delivered cost of ethanol was found to be \$1.20 per gallon.

and remains productive for approximately 10 years [80]). To overcome the computational challenge, special algorithms and decomposition methods should be developed and tested. Ref. [69] proposed several techniques for model size reduction of large-scale renewable production and supply chain networks. The proposed techniques were successful in reducing solution time significantly and study for 50 zones was demonstrated. Unfortunately the average-sized county has more than 500 zones and there were several operations in the supply chain that were not considered. Therefore, there is need for a technique that can handle large-scale problems comprising of all operation of BSC along with providing economic, environmental and social measures to the system. System wide optimization of BSC is also crucial. Therefore, it is important to consider complete biofuel/bioenergy supply chain. This also provides significant cost savings.

Simulation optimization approaches enables fast, inexpensive, and non-disruptive assessment of a large number of scenarios while providing decisions that can be implemented in a real world situation. This technique allows conducting detailed “What-if” analysis, and has become a popular tool in the industrial sector. With simulation it is possible to include various sources of uncertainty into the analysis. The BSC is complex and difficult to be modeled as a pure mathematical formulation. The pure optimization models are not capable of capturing all the uncertain

Table 16
Assumptions, restrictions, and future work of the reviewed articles.

Ref.	Assumptions, restrictions and future work
[35]	**Assumptions:** Biomass can be stored for any number of time periods; the covered storage site capacity was not weather dependent; no interaction between storage sites associated with each producer; harvesting equipment was always available for all harvest schedules. **Restrictions:** The model provides a fixed modeling framework and might not be able to capture more complex supply chain design and operations. **Future work:** Introduce weather dependent average yield reduction factors and binary variables for minimum expansion of the storage site if it occurs.
[41]	**Restrictions:** The model was not dynamic and ignores seasonality; the model formulation was not reported in detail. **Future work:** Incorporate storage losses and inventory equations addressing storage at a node for more than one period; develop a multiple criterion optimization models.
[12]	**Assumptions:** All investments were made at beginning of 15 year life of biorefinery; a minimum inventory at biorefinery site was maintained; in-field storage inventory can be zero; land-owners were willing to engage in long-term leases for biomass production. **Restrictions:** Biomass yield and production cost yearly adjustments were not modeled; feasibility of gasification–fermentation technology and influence of the local, state, and federal legislation constraints on feedstock production and feedstock processing were not evaluated. **Future work:** Incorporate biomass yield and nutrient content variation by month of harvest for each feedstock and determine precise values for biomass storage losses.
[53]	**Assumptions:** Combined collection from multiple fields and 30 day drying period for cotton stalks. **Future work:** Evaluate model for other biomass feedstocks and more test cases to refine the model; conduct investment analysis to evaluate the potential benefits of the overall proposed system.
[54]	**Future work:** Incorporate local energy production policies into the model; Evaluate technologies that can enhance energy production by decreasing cost and environmental impacts should be done; develop, calibrate, and incorporate biomass growth dynamics model in the BSC model; develop a dynamic optimization approach to provide better estimates; Consider different types of conversion technologies such as gasification which have higher efficiency and environmental externalities.
[55]	**Assumptions:** No storage capacity for saw mills; the terminals at harbor and heating plants considered no chipping operation and no storage capacity, respectively.
[25]	**Assumptions:** Ethanol from cellulosic biomass was developed industrial sector with large-scale commercial production; initially ethanol used for low-level blends but as production increases high-level blends were used; Agricultural Statistical Districts (ASD) areas which could not meet the minimum capacity defined for plant base size were not considered; for some of the ASDs with capacity to support multiple base plants, only one plant with all capacity was modeled; all plants use same conversion technology. **Restrictions:** The operations other than transportation involved in supplying biomass were not considered. These operations could have significant impact on overall cost and network design of BSC.
[56]	**Assumptions:** Similar assumptions as made by [12] were considered; feedstock availability was only limited to CRP acres; CRP acres were available for bioethanol production; no fertilizers were required to maintain productivity; the harvest days were restricted to 30 days in Kansas, 60 days in Oklahoma, and 87 days in Texas. **Restrictions:** A specific conversion technology was not considered and the estimates for costs were based on 2004 price levels.
[57]	**Assumptions:** The cost data was taken from already published work and in some cases the data was for a different crop. **Future work:** Incorporate the utility requirement parameters considering the impact of emissions into the model. This facilitates endogenous life-cycle analysis and help in development of multi-objective formulations.
[58]	**Assumptions:** Different feedstocks can be processed at a single biorefinery; each feedstock has same value to the biorefinery. **Future work:** Incorporate precise estimates on number of harvest days in the model.
[31]	**Assumptions:** No transportation among the nodes at the same echelon and transportation of product from each node of echelon to any node of the downstream echelons were considered. **Future work:** The extension of model to multi-level supply chains using multiple feedstocks along with evaluating tactical and operational decisions should be done.
[59]	**Assumptions:** Each year same quantity of material was harvested. **Restrictions:** The formulation is based on long-term planning but the decision variables are not time-dependent. **Future work:** Develop of accurate forest growth models; include accurate calculations of CO2 balance for all supply chain processes; model vegetation humidity variation.
[60]	**Assumptions:** Dry grind technology was considered for ethanol production; maximum quota was allotted to domestic production of biomass to avoid conflict of biomass vs. food. **Future work:** The application and extension of the model to second-generation bioethanol production technologies.
[61]	**Assumptions:** Biomass was available at the centroid of each parcel; each biomass type was harvested, collected, and transported in a linear pattern; closed storage sites were considered. **Future work:** Evaluate low cost storage option; include material and degradations losses and impact of uncertain factors into the model.
[26]	**Assumptions:** No inventory was held at the field site. **Future work:** Develop methodology to solve large-scale problems in reasonable time.
[62]	**Assumptions:** Homogeneous distribution of mallee biomass was considered.
[63]	**Assumptions:** Biorefinery will not shut down once it is open; model formulation allows the expansion of the biorefinery not reduction in capacity. **Future work:** Incorporate dynamic aspect of conversion technologies and policy standards into the model; consider uncertainty due to supply/demand, technology, and unexpected disruptions caused by natural and man-made disasters; use decomposition methods to deal with large-scale problems.
[18]	**Future work:** Incorporate and evaluate different conversion routes into the model.
[43]	**Assumptions:** The model was developed considering steady-state conditions.
[64]	**Assumptions:** Single plant of each processing type was selected from the different capacity options. **Future work:** Extension of the model to include more complex network structures considering more processing options and mobile processing infrastructure and multiple periods to account for the change in infrastructure with time; incorporate uncertainty in biomass supply and market into the model.
[51]	**Assumptions:** The biofuel industry can be integrated with existing bioenergy systems.
[65]	**Assumptions:** Biorefineries were accessible by both truck and trains; switchgrass source sites were accessible by truck only; the capacity of harvest units and price of fuel was same during harvesting and non-harvesting months. **Future work:** Adjustment of the model to weekly time periods so as to account for the varying switchgrass properties; consider the planning horizon for more than 1 year, as the life-cycle of switchgrass is 11 years and establishment period is 3 years; consider multiple biomass feedstocks.
[66]	**Assumptions:** Biomass was collected and stored in form of round bales; the biorefinery was considered to be eligible for the cellulosic Biofuel Producer Tax Credit and Volumetric Ethanol Excise Tax Credit; all the investment occurred in the present year and cash flow was same for lifetime of the biorefinery.
[67]	**Assumptions:** Single type of biofuel was produced from multiple biomass feedstocks; the conversion efficiency of biomass was based on some percentage of theoretical estimates; the material was stored before going into either pre-processing site or conversion facility site. **Future work:** Develop specialized algorithms to run large-scale problems; determine the relationship between the storage capacity and replenishment policy; consider different modes of transportation; develop stochastic models to deal with uncertainty; develop model that can be adapted according to the interest of specific stakeholder such as biomass supplier and biorefinery.
[68]	**Assumptions:** The background traffic flow was fixed and was independent of biomass and ethanol shipments. **Restrictions:** Overestimation of the transportation cost and congestion impact because background traffic, driver diversions, and roadway capacity expansion was not considered; the fixed cost component of transportation was not considered in the model. **Future work:** Consider the peak/off-peak hours of transportation for biomass with use of dynamic traffic assignment model; include different production technologies and biomass types in the model; Extension of the model to solve large-scale problems at regional and national level with multi-model transportation network or multi-year dynamic planning; extension of the model to demonstrate the export and domestic use of corn with the expansion of biofuel industry.
[49]	**Future work:** Develop a nation-wide case study which allows biomass feedstock and biofuels to be transported across the state borders; develop efficient decomposition algorithms to deal with large-scale problems; incorporate the capacity expansion along with supply and demand contracts in the model; include different types of uncertainty into the model such as demand fluctuations, biomass supply disruption, and changes in government policies and incentives.
[50]	**Future work:** Incorporate different types of uncertainty into the model such as demand fluctuations, biomass supply disruption, and changes in government policies and incentives; develop decomposition algorithms that can solve large-scale problems.
[69]	**Restrictions:** The parameter variations due to geographical and weather conditions were not considered.

Table 16 (*continued*)

Ref.	Assumptions, restrictions and future work
	Future work: Implementation of model for large-scale problems with more zones and entities; evaluate more alternatives with regard to vehicle selection and pre-treatment technologies; develop model with multi-objective optimization to compare different network structures; relax simple assumptions to get realistic and robust results.
[70]	**Assumptions:** The biorefineries were accessible by trucks and train; infinite storage capacity for in-field warehouse, the residue from biorefinery was transported only during return trips.
[71]	**Restrictions:** The availability of 5 biomass types was varied simultaneously rather than independently in the model. **Future work:** Develop a complex network structure with more processing options and mobile processing unit; extend the model to multiple periods; integrate the new biofuel infrastructure with the existing facilities such as wood and pulp processing plants in order to increase mass and energy efficiency.
[72]	**Assumptions:** The demand and technology was assumed to be static. **Restrictions:** The model considers only the recurrent risks but the non-recurrent risks such as catastrophic events were not considered. **Future work:** Develop stochastic multi-period BSC model.

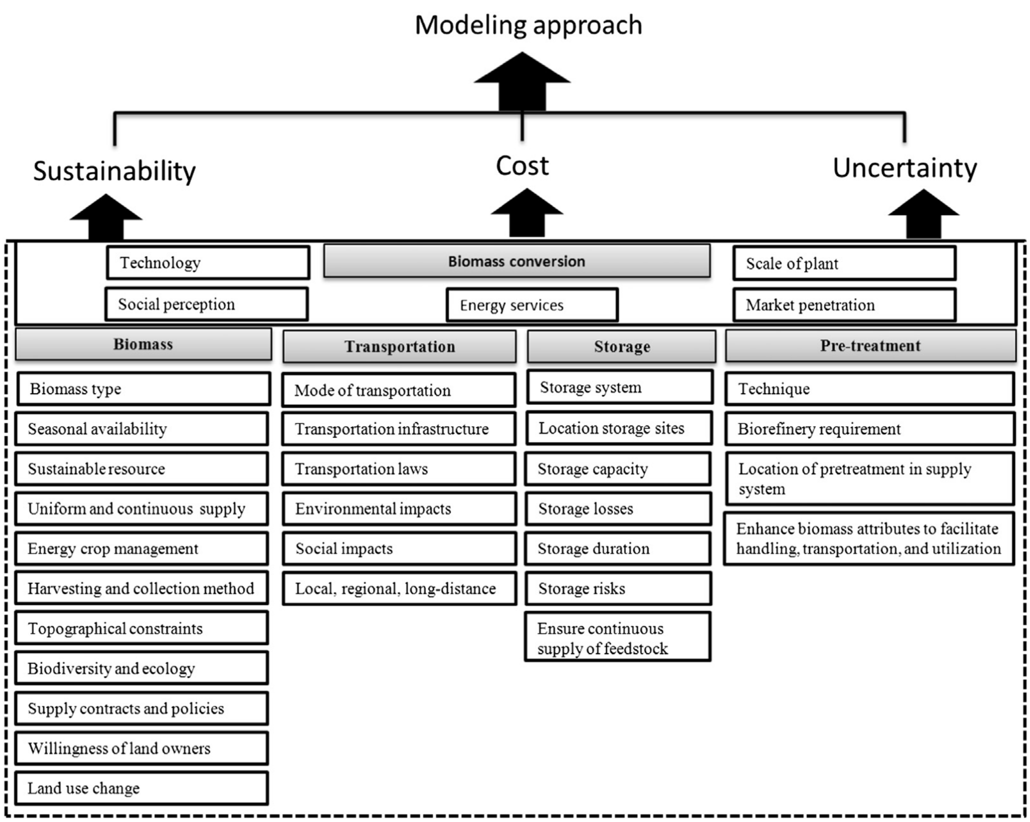


Fig. 11. Factor and considerations for developing modeling approach for BSC.

parameters and dynamics of the system. Simulation optimization provides solution to issues related to the BSC modeling by combining both the simulation and optimization techniques. Finally, it can be suggested that future work can be directed towards developing simulation optimization models for BSC providing the user with an especially useful and easy-to-use tool for identifying improved BSC decisions under risk and uncertainty for different stakeholders (biomass producers, processing plant owners, and policy makers).

5. Conclusion

This paper presented an exhaustive literature review on mathematical modeling of BSC. For the comprehensive analysis of reviewed work, a classification based on eight aspects was presented: decision level, supply chain structure, modeling approach, quantitative performance measure, shared information, novelty, practical application, assumptions, restrictions, and future work. The conclusions draw from the work affirm that (1) approximately 40.63% of the work on mathematical modeling in BSC was published in the year 2011; (2) the majority of works focused on strategic decisions related to location and capacity of plants, and network design. The tactical and operational decisions were related to material flow, inventory and fleet management. (3) most of the models reviewed had a network structure with biomass supply sites, collection sites and processing sites being the most common types of entities considered; (4) the most widely used modeling technique for BSC was the mixed integer linear programming model; (5) the purpose of the majority of models was cost minimization and the next most popular performance measure was revenue maximization; (6) the entities considered by almost all references were the biomass source sites, and processing sites. Some of the studies focused on an integrated view of BSC chain considering all the entities from biomass source sites to end-user/demand centers; (7) bioethanol was the end-product considered in most of the models; (8) it was observed that the modeling techniques and solution capabilities have improved significantly over the years; (9) the vast majority of the works presented

case studies applied to real situation to demonstrate the practical application of the model; (10) the future work will be directed towards developing models handling large-scale problems, uncertainty, and sustainability issues.

The review also presented the issues and challenges related to BSC modeling and proposed future lines of research. Four major areas were identified for future research: (1) incorporating uncertainty into the model formulation; (2) focusing on system wide modeling and optimization; (3) incorporating economic, environmental and social measures into the model; (4) addressing computational complexities and developing large-scale case studies for nationwide analysis; (5) developing models that can be easily adapted according to the interest of specific stakeholders such as biomass supplier and refinery owners. Finally, the techniques to deal with uncertainty were discussed, and simulation optimization technique was proposed for modeling BSC in future.

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